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HUBBLE SPACE TELESCOPE OBSERVATIONS OF THE VERY LOW MASS COMPANION TO GLIESE 105A

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ABSTRACT

Hubble Space Telescope images of the astrometric binary Gl 105A confirm the previous ground-based detection of a faint, very red companion (Gl 105C) located 3″39 from Gl 105A at P.A. 290°. The instrumental magnitudes of Gl 105C are $V_{555} = 16.86$ and $I_{814} = 13.54$. The observed position of Gl 105C differs significantly from the positions expected from current astrometric solutions. No other companions brighter than $I_{814} = 20.3$ are seen between 1″ and 13″5 from Gl 105A. Using the M dwarf model atmospheres of Allard and Hauschildt, we obtain for Gl 105C a standard color of $V - I = 4.6$, which suggests a spectral type of M7 V.

Subject headings: binaries: close — stars: individual (Gliese 105A) — stars: low-mass, brown dwarfs

1. INTRODUCTION

The astrometric binary Gl 105A (HR 753, HD 16160, BD + 6°398; $V = 5.81$; spectral type K3 V) has been the subject of two long-term studies conducted at Sproul Observatory (Lippincott 1973; Heintz & Cantor 1994) and McCormick Observatory (Martin & Ianna 1975; Ianna 1992). Both groups observe an orbital period of ~60 yr and conclude that the unseen companion has very low mass (0.08–0.13 $M_\odot$). Attempts to resolve the companion visually (Lippincott 1973; Heintz & Cantor 1994) and by optical or infrared speckle interferometry (McAlister 1978; Hartkopf & McAlister 1984; McCarthy 1995) have been unsuccessful. Using an optical coronagraph and the Palomar Observatory 60 inch telescope, Golimowski et al. (1995, hereafter GNKO) detected a faint ($I = 12.6$), very red ($R - I = 3.7$) companion, Gl 105C, located 3″27 from Gl 105A. They concluded from empirical color-luminosity and mass-luminosity relations that Gl 105C has a mass of 0.084 $M_\odot$, which is just above the 0.08 $M_\odot$ minimum for stable hydrogen burning (D'Antona & Mazzitelli 1985).

We have observed Gl 105A with the *Hubble Space Telescope* (*HST*) as part of a Guaranteed Time Observer program whose principal aim is the detection of extrasolar planets around stars within 5 pc of the Sun. Originally intended to commence after the launch of *HST* in 1990, this program was postponed until the repair of the telescope was successfully completed in 1994. From the beginning, our program has included three astrometric binaries, Gl 105A, 36 UMa A, and Barnard's Star, which were recommended by the late R. S. Harrington as stars with possible very low mass (VLM) companions. This Letter describes the first result of our program, and its content sustains the foresight of our former colleague.

2. OBSERVATIONS AND DATA REDUCTION

Gl 105A was first observed on 1995 January 5 using the Wide Field and Planetary Camera 2 (WFPC2) aboard *HST*. The star was acquired at the approximate center of the unvignetted region of the Planetary Camera (PC), providing a 33″5 × 33″5 field of view centered on the star. Only the PC was read out after each exposure. Images were obtained using the F555W and F814W filters, which are the designated WFPC2 V and I passbands, respectively (Burrows et al. 1994). Four 35 s exposures were recorded through F555W, and eight 35 s exposures were recorded through F814W. During each exposure, approximately 10^9 photons from Gl 105A were detected. Each image of Gl 105A was therefore saturated near its center, but good data were obtained beyond 1″ from the star except where excess charge had overflowed the saturated pixels. Gl 105C was not expected to saturate the detector in 35 s using F555W, but four 1 s exposures were taken through F814W to ensure unsaturated exposure of Gl 105C in that passband. All exposures were recorded using a gain of 14 e DN^{-1}. During the exposures, the pixels in the PC's serial register were continually clocked to minimize the effect of charge overflow.

A follow-up series of eight 35 s exposures through F814W was recorded on 1995 February 10 to confirm the common proper motion of Gl 105A, Gl 105C, and any other potential companions identified after the January observation. To ensure that the instrumental point spread function (PSF) was the same for each observation, Gl 105A was acquired at the same location and orientation during each visit. This task was accomplished by duplicating the spacecraft roll used on 1995 January 5 and by compensating for the proper motion and parallax of Gl 105A over 35 days.

The images were reduced using the Space Telescope Science Data Analysis System (STSDAS) software and the calibration reference files recommended by the *HST* data archive on 1995 March 1. The calibrated images were scaled to correct for the 0.125 or 0.250 s exposure-time errors caused by the concurrent activation of the WFPC2 shutter blades and the PC serial clocks (Baggett 1995). Each set of exposures was combined to form two single images representing the median and average of the set. The median image, being free of cosmic-ray artifacts, was used both to determine the positions of Gl 105A and Gl 105C and to search for fainter companions. Both the median and average images were used for photometry, the latter serving as a check for possible drift of the telescope between exposures. No drift was detected.

3. RESULTS

Figure 1 (Plate L23) shows the central 9″ × 9″ sections of the median 35 s F555W and 1 s F814W images of Gl 105A obtained on 1995 January 5. Evident in both images are the diffraction spikes caused by the *HST* + PC secondary-mirror

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spider and the charge overflow from the saturated pixels near Gl 105A. The stellar source located west-northwest of Gl 105A and adjacent to the charge overflow in the F555W image is the same source identified by GNKO as the companion, Gl 105C. The source was also seen in the 1995 February 10 follow-up images (not reproduced here) at the same location relative to Gl 105A.

3.1. *Relative Astrometry*

To determine accurately the position of the saturated image of Gl 105A, the intersection of the diffraction spikes seen in each 35 s median image was computed using the coordinates of 50 pixels lying along the midline of each spike. With this technique, the center of the Gl 105A image could be determined to within 0.5 pixel. To obtain accurate astrometry and photometry of Gl 105C, subtraction of the primary star's PSF was required. A synthetic PSF was created using two 40th-order Legendre polynomials fitted to the radial profiles of the observed PSF at orientations 4°–10° to either side of Gl 105C. For each pixel within this azimuthal range, a weighted average of the two best-fit polynomials was computed and subtracted. The subtraction of the PSF near Gl 105C was nearly complete: the photometric uncertainty due to subtraction error is less than 0.5% of the integrated flux from the companion. The resulting centroid of the Gl 105C image was determined to within a radius of ± 0.06 pixel ($\pm 0\farcs003$).

Using a PC pixel size of $0\farcs04553$, Gl 105C was found in the 1995 January 5 images to be $3\farcs389 \pm 0\farcs019$ from Gl 105A at P.A. $289\fdg9 \pm 0\fdg2$. These coordinates agree with those reported by GNKO and are an order of magnitude more certain. Because Gl 105C was saturated in the 35 s F814W follow-up images, precise measurement of its relative position was not possible. To measure any changes in the position of Gl 105C between visits, the median F814W images were aligned by cross correlating the primary star's PSF in increments of 0.125 pixel. (The saturated pixels were masked to prevent skew statistics.) The resulting positions of Gl 105C agreed to within 1 pixel. Since the proper motion of Gl 105A over the 35 days between visits was $0\farcs222$ (4.9 pixels), the common proper motion of Gl 105C is confirmed.

3.2. *Search for Fainter Companions*

As depicted in Figure 2 of GNKO, the position of Gl 105C differs by $4\farcs1$ and $2\farcs8$, respectively, from the positions of the astrometric companion expected from the best-fit photocentric orbits of Ianna (1992) and Heintz & Cantor (1994). To satisfy both the 60 yr astrometric period and our observations, either Gl 105C must be at apastron in a radically eccentric orbit or other astrometric companions must exist. The former scenario contradicts the astrometric solutions, both of which indicate a companion presently near periastron in a less eccentric orbit. We now investigate the latter scenario.

Visual inspection of the median 35 s F555W and F814W images revealed one other starlike source lying $\sim 17''$ to the east-southeast of Gl 105A. The relative motion of this source between visits indicates that the source lies in the distant background and is unassociated with the Gl 105 system. To search systematically for fainter companions, we required a technique that accommodates the changing background signal from Gl 105A. Conventional subtraction of this background was not feasible because we lacked a control star image. Therefore, we flattened the background by dividing each pixel by r^{-n}, the radial power law best describing the PSF at that pixel location. Within 5" of Gl 105A, $n \approx 3$; beyond 5", $n \approx 2$. We then applied a search algorithm that identifies sources having four or more pixels brighter than a given threshold above the local rms deviation.

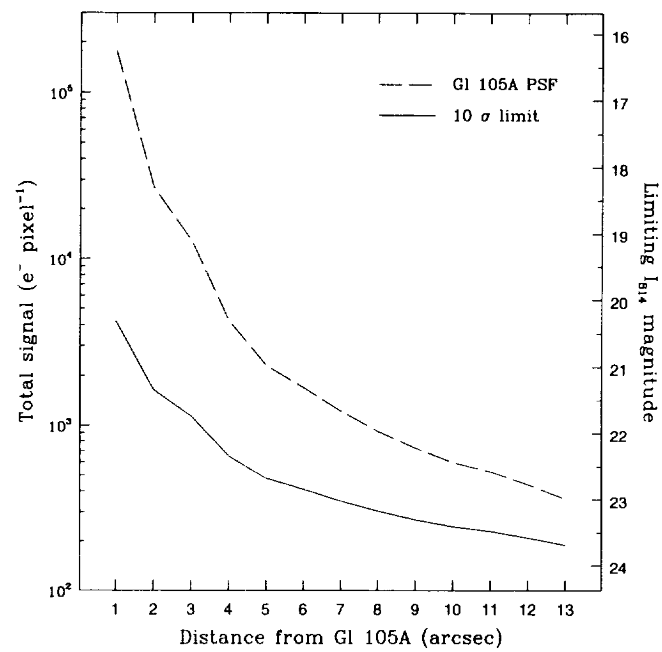

FIG. 2.—Signal and magnitude detection limits for a starlike source around Gl 105A (*solid curve*). The limits are based upon the total signal from Gl 105A obtained in eight 35 s exposures through F814W (*dashed curve*). The magnitude limit is defined as the brightness of a source producing four pixels equal to the 10 σ signal limit.

The dashed curve in Figure 2 shows the azimuthally averaged PSF recorded through F814W and sampled in 5×5 pixel arrays at 1" radial intervals. We avoided azimuths within 30° of the diffraction spikes, the charge overflow, and Gl 105C. (The bump at $\sim 3''$ is therefore not caused by Gl 105C.) The solid curve traces the signal level equal to 10 times the local background noise. Using this 10 σ level as a detection criterion, we searched the 35 s median images for possible companions lying within the $27'' \times 27''$ region centered on Gl 105A. We identified no starlike sources (other than Gl 105C) brighter than the local 10 σ level.

3.3. *Photometry of Gl 105C*

Using the instrumental sensitivities computed by the STSDAS calibration software, we obtain for Gl 105C the WFPC2 magnitudes $V_{555} = 16.86 \pm 0.01$ and $I_{814} = 13.54 \pm 0.01$. The uncertainties reflect only the combined effects of the PSF subtraction and photon noise. Combining these measurements yields $V_{555} - I_{814} = 3.32 \pm 0.01$.

To interpret the WFPC2 color of Gl 105C in the context of empirical color-magnitude and mass-luminosity relations for low-mass stars (Leggett 1992; Henry & McCarthy 1993), a transformation to Johnson-Cousins $V - I$ is required. We obtained this transformation using the WFPC2 system response functions (Burrows et al. 1994), the standard *VRI* passbands (Bessell 1990a), and the "base" model spectra of VLM dwarfs, subdwarfs, and brown dwarfs created by Allard & Hauschildt (1995). Figure 3 shows the V and I passbands of

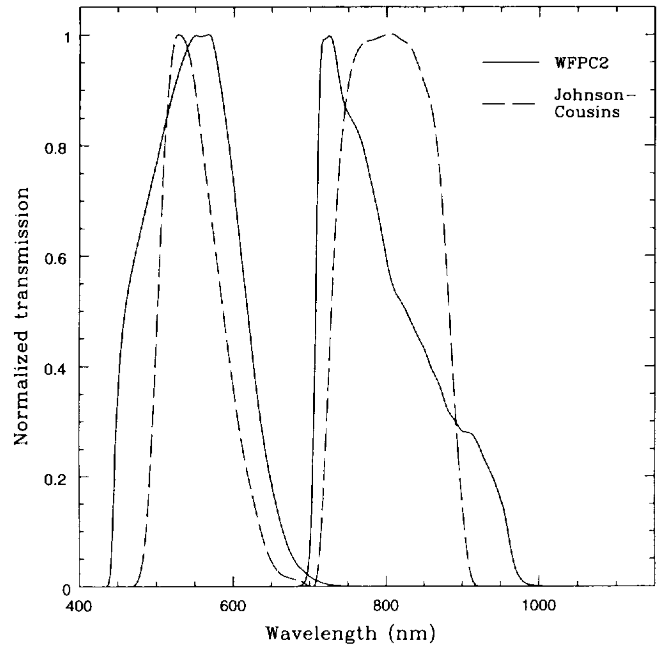

FIG. 3.—V and I passbands of the WFPC2 (*solid curves*) and Johnson-Cousins (*dashed curves*) photometric systems. The WFPC2 F555W and F814W system responses are from Burrows et al. (1994). The Johnson-Cousins V and I responses are from Bessell (1990a). Each passband has been normalized to unity at peak transmission.

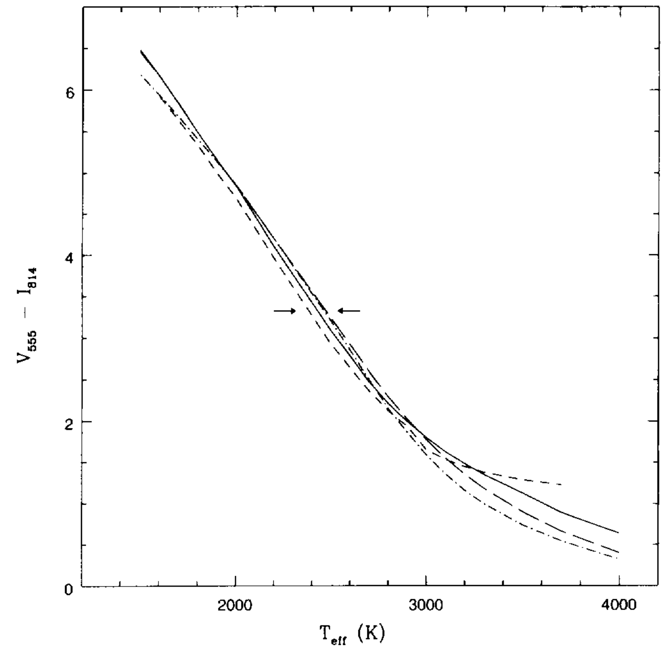

FIG. 4.—WFPC2 $V_{555} - I_{814}$ vs. T_{eff} for cool dwarfs with log (g) = 5.0 and varying metallicity. Shown are [M/H] = 0.0 (*solid curve*), +0.5 (*short dashed curve*), −0.5 (*long dashed curve*), and −1.0 (*dash dotted curve*). The arrows identify the range of T_{eff} associated with the measured $V_{555} - I_{555} = 3.32$ for Gl 105C. The curves are based on the VLM model atmospheres of Allard & Hauschildt (1995) and the WFPC2 passbands shown in Fig. 3.

each photometric system. We checked our transformation code for consistency with the STSDAS synthetic photometry software using the STSDAS composite energy spectrum of Vega. Our code correctly reproduced the WFPC2 magnitudes of $V_{555} = -0.013$ and $I_{814} = 1.217$ for Vega. The *VRI* passbands were then appropriately normalized to produce the Johnson-Cousins magnitudes for Vega reported by Bessell (1990b).

The atmospheric models of Allard & Hauschildt (1995) are parameterized by effective temperature (T_{eff}), surface gravity (g), and metallicity ([M/H]). We computed the WFPC2 colors for models with $1500 \le T_{eff} \le 4000$ K, $3.5 \le \log(g) \le 5.5$, and $-1.0 \le [M/H] \le +0.5$. Figure 4 shows $V_{555} - I_{814}$ versus T_{eff} for log (g) = 5.0 and varying [M/H]. Figure 5 shows the same for solar metallicity ([M/H] = 0.0) and varying log (g). Both figures reveal that $V_{555} - I_{814}$ rises steeply as T_{eff} decreases below 3000 K, and that for $2000 < T_{eff} < 3000$ K, the color is insensitive to [M/H] and log (g). For Gl 105C, we may reasonably assume log (g) ≈ 5 (Kirkpatrick et al. 1993b) and the same metallicity measured for Gl 105A ([Fe/H] = −0.25; Eggen 1987). Using these values and the measured $V_{555} - I_{814} = 3.32$, we interpolate from the models an effective temperature of 2450 K for Gl 105C.

After scaling each model spectrum to produce a synthetic V_{555} equal to that observed for Gl 105C, the Johnson-Cousins magnitudes for each model were computed. For $T_{eff} = 2450$ K, [M/H] = −0.25 and log (g) = 5.0, we obtain $V = 16.9$, $V - R = 2.1$, and $V - I = 4.6$. These colors match those observed for the M7 V star Gl 644C (Leggett 1992). The synthetic I agrees well with the $I = 12.6$ measured for Gl 105C by GNKO, but R is 1.5 mag smaller than that measured by GNKO.

4. DISCUSSION

The $T_{eff} = 2450$ K deduced from the base models of Allard & Hauschildt (1995) places Gl 105C between the brown dwarf candidate GD 165B (2250–2350 K) and the M9 dwarf LHS

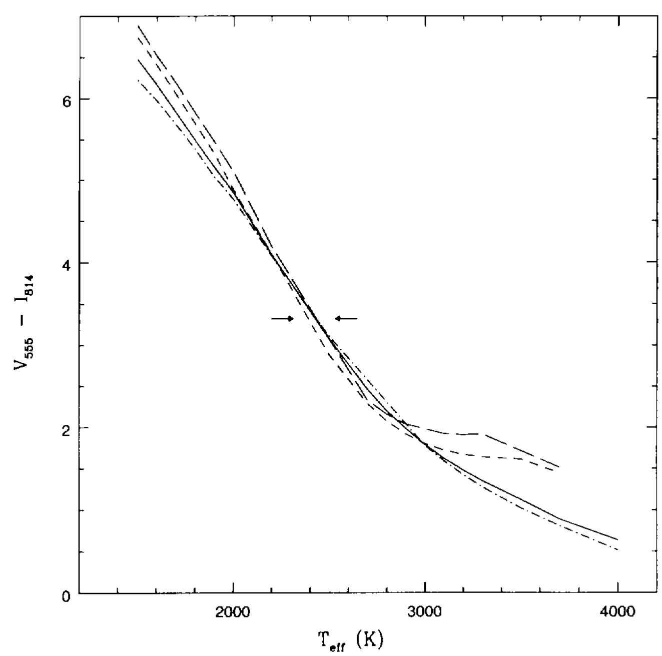

FIG. 5.—WFPC2 $V_{555} - I_{814}$ vs. T_{eff} for cool dwarfs with [M/H] = 0.0 (solar) and varying surface gravity. Shown are log (g) = 5.0 (*solid curve*), 3.5 (*long dashed curve*), 4.0 (*short dashed curve*), and 5.5 (*dash dotted curve*). The arrows and curves are explained in Figure 4.

2924 (2625 K) on the list of coolest known dwarfs (Kirkpatrick et al. 1993a). This temperature, however, contradicts the M7V spectral type inferred from the synthetic colors. Baraffe et al. (1995) have noted that, for stars with $M_V > 15$, the base models yield photospheric temperatures that are at least 200 K too large for a given luminosity (i.e., too small for a given $V - I$) because of overestimated molecular opacities. Thus, temperatures obtained with these models must be treated with caution. On the other hand, our color transformation and inferred M7 V spectral type are probably accurate since $T_{\rm eff}$ is not constrained and $V - I$ is insensitive to both [M/H] and $\log(g)$.

The Gl 105 system provides a rare opportunity to determine unambiguously both the mass and spectral type of an object near the stellar-substellar boundary. In principle, our measurement of the separation of the astrometric binary is sufficient to derive the masses of both components. However, current descriptions of Gl 105A's photocentric orbit differ significantly and fail to predict the observed position of Gl 105C. Thus, long-term direct observations are needed to better determine both the relative orbit and the mass of Gl 105C.

Kirkpatrick & McCarthy (1994) have established an empirical relation between dynamic mass and spectral type for dwarfs as cool as M6.5. This relation suggests that M7 dwarfs spectrally define the boundary between the M dwarf and brown dwarf populations. Confirmation of Gl 105C's inferred mass of 0.084 $M_\odot$ (GNKO) and M7 V spectral type (this work) would not only support this suggestion, but also imply that later-type objects like GD 165B or LHS 2924 are in fact brown dwarfs.

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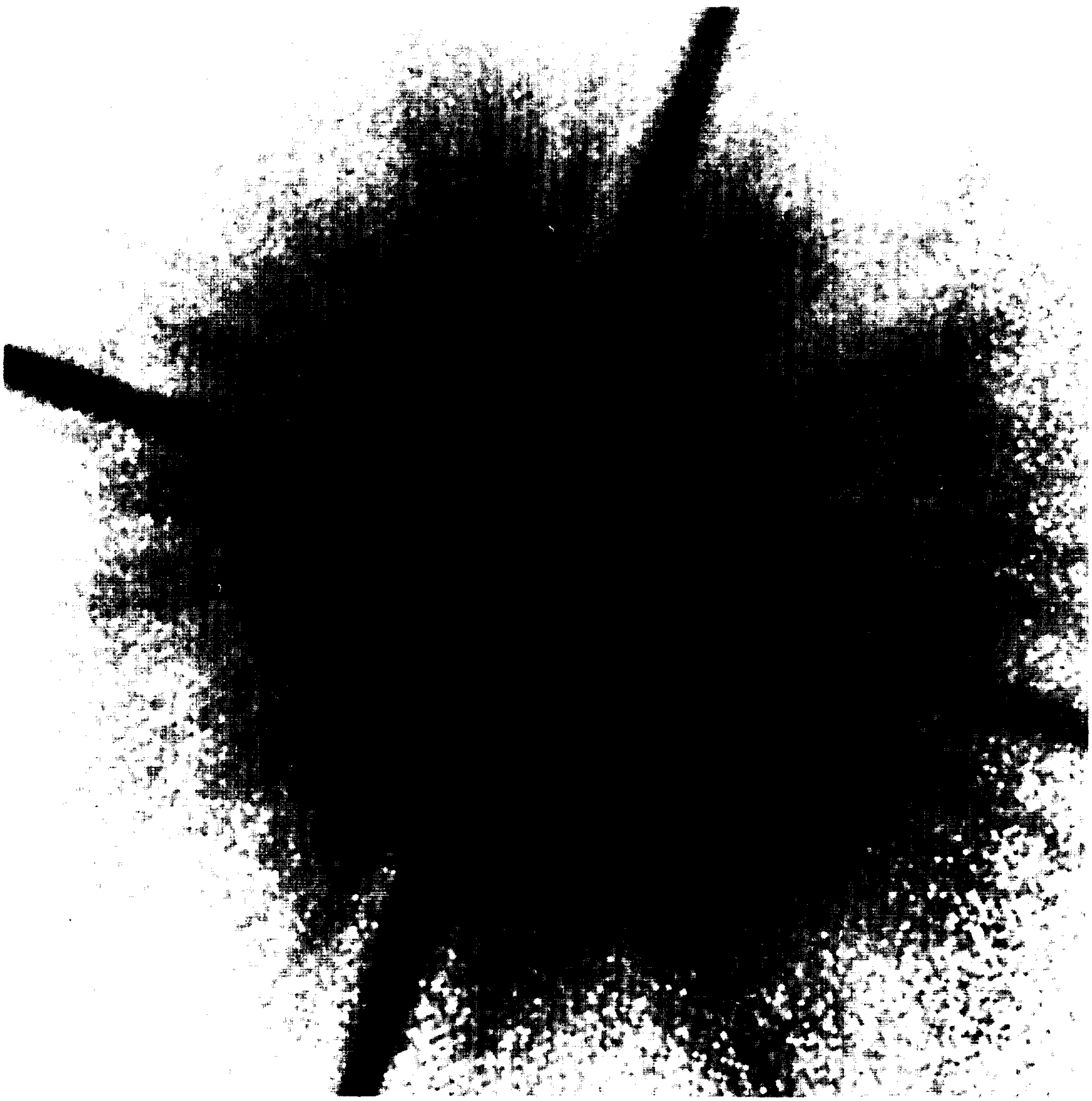

FIG. 1*b*

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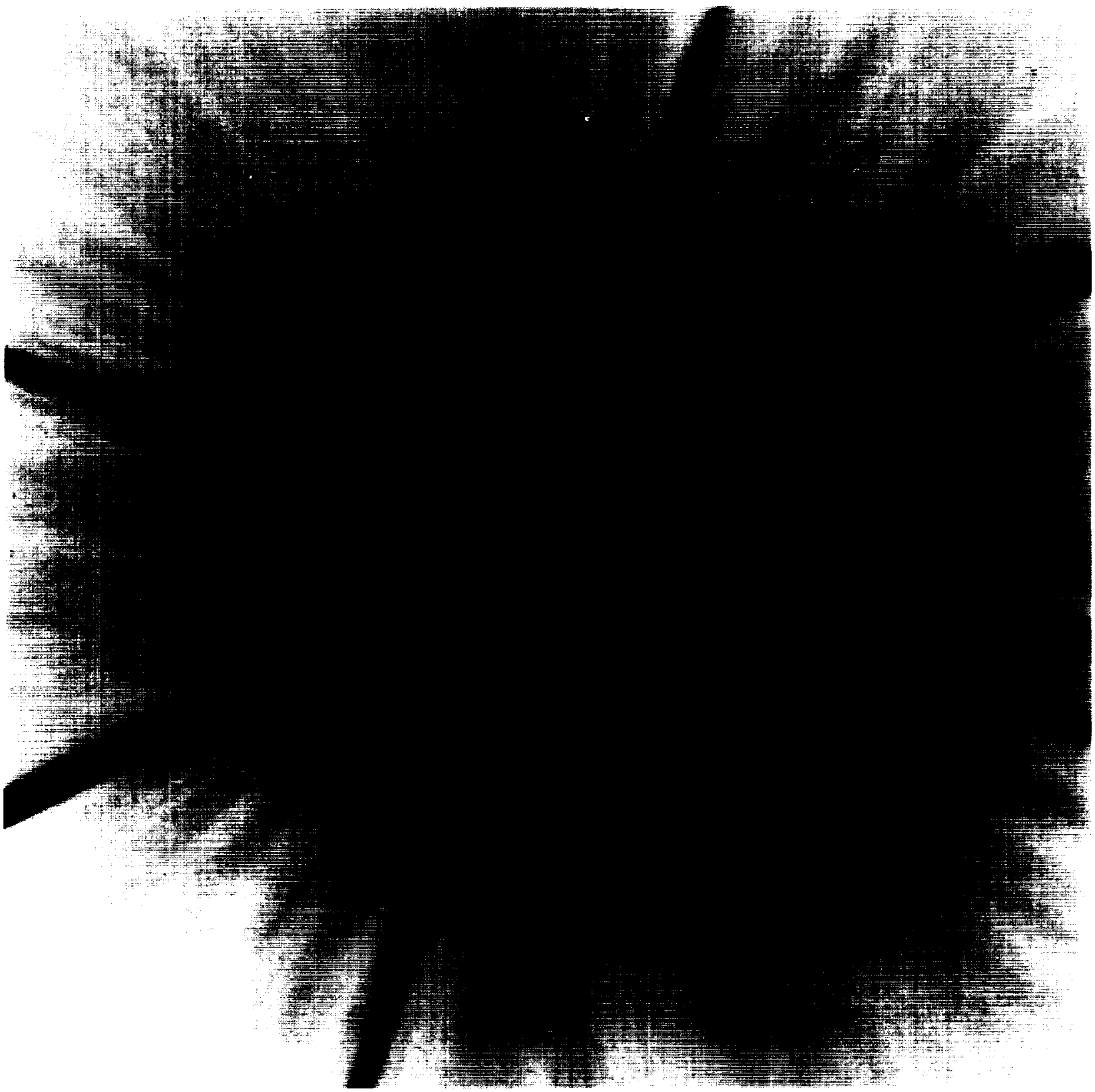

FIG. 1*a*

FIG. 1.—Images of the K3 V astrometric binary Gl 105A obtained on 1995 January 5 with the *HST* Planetary Camera. (The logarithm of the data is presented to limit image contrast.) The field of view is 9″ × 9″, with north at the top and east to the left. Gl 105A ($V = 5.81$) appears overexposed. The faint companion, Gl 105C, is seen 3″.39 from Gl 105A at P.A. 290°. (*a*) Median of four 35 s exposures taken through the F555W filter (WFPC2 V). The companion has a brightness of $V_{555} = 16.86$. (*b*) Median of four 1 s exposures taken through the F814W filter (WFPC2 I). The companion has an I_{814} magnitude of 13.54.

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